A computer program that evaluates the effect of changes in legal load limits on the life-cycle costs of flexible, rigid, and composite pavements is described. The methodology of the NULOAD program for determining the effects of changes in truck size, weight, and configuration on pavement performance is examined, and these effects are related to maintenance and rehabilitation and their related costs. A sample problem from NULOAD is also discussed. Fifty representative sections can be grouped by type of system (such as Interstate sections) to reflect the effect of traffic loadings on the different classes of highways. The procedure permits inclusion of a maximum of 10 different truck types along with various axle and tire configurations, such as single axles with single tires and tandem-axle configurations. Truck axle weight and configuration are the major variables considered, but the procedure can also handle new sizes of trucks, such as the triple-trailer units. The procedure also includes a computerized shifting procedure for gross vehicle weight and axle-load distribution.

This paper describes the development and use of a methodology for determining the effects of changes in truck size, weight, and configuration on pavement performance and relating these effects to pavement maintenance and rehabilitation and their related costs. The procedure was developed under a Federal Highway Administration (FHWA) project and is documented in the project final reports (1,2). The objectives of this paper are

1. To provide a summary description of the evaluation procedure,
2. To describe the necessary input data for use of the procedure, and
3. To discuss an illustrative example run from the computerized procedure NULOAD.

SCOPE OF THE PROCEDURE

The NULOAD procedure evaluates the effect of changes in legal load limits on the life-cycle costs of flexible, rigid, and composite pavements. Fifty representative sections can be grouped by system (e.g., Interstate sections) to reflect the effect of traffic loadings on the different classes of highways. The procedure permits inclusion of a maximum of 10 truck types along with various axle and tire configurations, such as single axles with single tires or tandem axles, as well as conventional single- and tandem-axle configurations. Although truck axle weight and configuration are the major variables considered, new truck sizes, such as the triple-trailer units, can be handled in the procedure. The procedure includes a computerized shifting procedure for gross vehicle weight (GVW) and axle-load distribution that was first proposed by Whiteside and others (3). The user can select different representative sections. The cost predictions are prepared for any number of lane kilometers in each representative section so that evaluations at a variety of governmental levels can be performed. The procedure also uses a distribution by age and lane kilometers for each representative section.

EVALUATION CONCEPTS

The evaluation procedure permits estimates of costs associated with changes in routine maintenance and rehabilitation requirements that result from changes in the legal load limits. The four basic sets of computations included in the procedure are displayed graphically in the conceptual flowchart shown in Figure 1. They include

1. Determining the traffic loading in terms of 80-kkn (18 000-lbf (18-kip)) equivalent single-axle loads (ESALs) for both present and proposed legal limits, including a load-distribution shifting procedure;
2. Predicting the expected life cycles of pavements of each age of the distributions by age and lane kilometers for all representative sections, including rate of deterioration, time of overlay, and overlay requirements;
3. Estimating the associated minor maintenance and rehabilitation (overlay) costs for all representative sections; and
4. Printing a summary of the cost and performance estimates by section, system, and/or entire network as specified by the user.

The life-cycle estimates are based on American Association of State Highway and Transportation Officials (AASHTO) performance equations (4). The overlay thickness is determined from the section condition (present serviceability index (PSI)) at the time of overlay and expected traffic for a 20-year overlay design life. In initial calculations, provision is made for considering the differences in AASHTO performance predictions and experience in the state through the use of average pavement ages at terminal serviceability and the application of "Iowa-type" survivor curves (5).

For each representative section, the user can consider routine maintenance costs in one of three ways: (a) not at all, if the user suspects that maintenance costs will not change with new loads; (b) by using cost-prediction models obtained from the EAROMAR program (6); or (c) based on historical cost information obtained from highway department records.

PROGRAM CAPABILITY

The NULOAD program has the capability to model various sizes of highway networks for which input data can be developed. The kilometers of a network should be distributed based on system classification (Interstate urban, Interstate rural, primary urban, and so on), section structure (asphalt concrete, portland cement concrete, or composite), and pavement age (time since construction or major reconstruction). A network can be divided into as many representative structural sections as necessary to adequately characterize the network. The lane kilometers of each representative section are distributed by pavement age.

The major capabilities of NULOAD include

1. The ability to handle as many as 10 representative sections for each system;
2. The ability to make predictions on the assumption either that the same total payload per year is car-
ried under present and proposed limits or that the same number of truck trips per year is made under both limits;
3. The choice of different maintenance cost models for each representative section;
4. Consideration of a traffic-stream mix of up to 10 trucks for both present and proposed regulations;
5. Variation in the percentage of each truck type as a percentage of all vehicles, by year in the analysis period;
6. The use of predictions of pavement performance that are based not only on pavement structure and traffic but also on existing pavement age;
7. A prediction of overlay cost, including the necessary costs to bring the shoulders up;
8. An estimate of remaining network functional life in terms of 80-kN ESALs to provide a measure of the structural condition of the system at the end of the analysis period;
9. Prediction and summarization by section, by system classification, and for the entire network of the expected economic effects of various proposed changes in legal load limits on maintenance and rehabilitation;
10. A number of options available to the user for handling those pavements in the category of pavements older than terminal serviceability (POTS), i.e., pavements in such poor condition that the PSI at the beginning of the analysis period is below the terminal level;
11. Problem stacking for solution of many problems through the flexible input order of the NULOAD program;
12. The ability to consider asphalt concrete, portland cement concrete, and composite pavements in a single set of runs;
13. A provision to consider differences between AASHTO performance predictions and state experience through the use of various age parameters at terminal serviceability in conjunction with the use of Iowa survivor curves (5);
14. The ability to model the effect of different and multiple-trailer configurations by using vehicle designations and equivalency factors for single, tandem, and tridem axles; and
15. A slightly modified version of the load-distribution shifting procedure reported by White and others (3).

SUMMARY OF REQUIRED INPUT

Although no special field or laboratory studies are required, the use of NULOAD requires many data from highway agency records. The information required to determine input values for NULOAD is summarized as follows:

1. Traffic and load survey information includes decomposition of the traffic stream; truck types; single, tandem-, tridem-, and steering-axle-load distributions; GVV distributions; empty vehicle weight; legal limits and expected growth in 80-kN ESALs.
2. Performance-prediction information includes highway network statistics, especially the kilometer breakdown by pavement type and age and system classification; representative design section structural information, including materials parameters and thicknesses and soil-support information; and performance parameters, such as regional factor, serviceability limits, an average pavement age at terminal PSI, and pavement ages when 25 and 75 percent of the length of each representative section should reach terminal PSI.
3. Economic prediction data include unit cost information, historical maintenance expenditures, geometric dimensions, interest rates, and pavement types.

The sample problem discussed in this paper uses realistic values for input, but specific data should be developed for each prediction desired.

DESCRIPTION OF THE PROCEDURE

The NULOAD computer program has been developed to use information currently available to state departments.
of transportation. These data are used as input to the AASHTO performance model (4), the weight–distribution shifting procedures developed and included as a part of NCHRP Report 141 (3), and maintenance models from EAROMAR (6) to evaluate the difference in the life-cycle costs for the two different legal load limits selected by the user. The major calculation subsystems of the NULOAD procedure are discussed briefly in the following sections of this paper.

Remaining Life and Rehabilitation Calculations

NULOAD uses the performance equations from the AASHTO Interim Guide (4) as a basis for calculating the number of 80-kN ESALs that a typical representative section can withstand before reaching terminal PSI. At terminal PSI, the section under consideration can be overlaid in a timely manner or allowed to go below the prescribed PSI level—i.e., enter into the POTTS program. If the section enters POTTS, the layer coefficients are reduced in a manner prescribed by the Asphalt Institute (7, Table III-1). These reductions in the value of the layer coefficients were made to correspond to the different terminal PSI values in common use.

The kilometers of a particular age that require overlay rehabilitation during each of the years of the analysis period are determined by using a symmetrical type of Iowa survivor curve (5). One modification has been made to the application of these curves to enhance computer operations. This modification involves the assumption that the survivor curve for the pavement surface will not span a period of more than 13 years centered about the average life of the section. For example, if a representative section has an average life of 15 years, the life of various projects could be expected to range from 8.5 to 21.5 years, but most would require rehabilitation at around 15 years. The exact number of kilometers of pavement sections of a certain age that are reaching terminal PSI will be a function of the average age at terminal PSI and the standard deviation of the survivor curve. These concepts are discussed in more detail in the following sections.

AASHTO Performance Equation

The structural design equations for both flexible and rigid pavements developed at the AASHO Road Test are the basis of calculating the number of 80-kN ESALs that the typical pavement structure will sustain before reaching terminal PSI. This is accomplished by substituting the individual layer thicknesses and structural layer coefficients, a typical regional factor, and a typical soil-support value into the AASHTO equation. The total cumulative 80-kN ESAL is assumed to be applied over the years between initial construction and the average age before the pavement structure reaches terminal PSI (P). By using this average age at P, total cumulative ESAL, and the average growth rate of ESAL, NULOAD computes the rate of 80-kN ESAL applications per year and the number of ESALs remaining at the beginning of the analysis period on each pavement age of the distribution by age and lane kilometers. Traffic during the analysis period is applied at the calculated rate so that the pavement reaches P at the average age at P. The traffic level at the year of the analysis period when PSI reaches P is used along with the anticipated growth rate to calculate the number of 80-kN ESALs to which an overlay on the existing pavement will be subjected during its design life.

If the overlay is applied in a timely manner and if the P, is 3.0, the structural coefficients assigned to the existing pavement are only slightly reduced when overlay thicknesses are calculated. However, for kilometers of pavement that are permitted to go below a selected value of P,—i.e., pavement kilometers in POTTS—the structural coefficients are also reduced to reflect the decreased resistance of the structure to loads because of the effects of surface deterioration and the effects of moisture on the underlying layers and subgrade. Structural coefficients are increasingly reduced from their original values as the terminal PSI values decrease from 3.0 toward the commonly used values of 2.5 and 2.0. The overlay thickness required for the present load limits is calculated by using estimated future traffic, the appropriately reduced structural coefficients of the layers, and the typical soil-support value.

Use of Survivor Curves

The use of survivor curves is a standard method of making management decisions relative to future estimates of time to retirement of physical properties. Physical properties are said to be retired from service when, for one reason or another, they are removed from productive service or altered and used in a second service life (6). Winfrey (8) has developed 18 different survivor curves that fit into the three basic types: symmetrical, left modal, and right modal. The type selected for use in NULOAD is the symmetrical; the standard deviation of the survivor curve is defined by user input.

The application of these survivor curves in NULOAD can best be discussed by using an illustration. The upper part of Figure 2 shows the performance of a pavement that enters the analysis period at a PSI of 3.5 and reaches the terminal PSI (P) of 2.5 during the 10th year of the analysis period, the average age of the pavement at P. In the lower part of Figure 2, the histogram shows the kilometers of pavement that reach P, at each of the 13 years centered about the average age of P, by using the symmetric survivor-curve concept. These kilometers are calculated, by using the survivor curve, by first computing the probability that some number of kilometers will reach P, and then this probability is multiplied times the total pavement kilometers of that age. These probabilities are calculated by using the average age at terminal PSI and the standard deviation calculated from the following two input quantities:

(a) the expected age by which 25 percent of the pavements have reached P, and (b) the expected age by which 75 percent of the pavements have reached P. These kilometers of pavement are then either scheduled for overlay during the assigned years of the analysis period or placed into POTTS, depending on user-specified inputs.

The process discussed above is repeated once for each pavement age—i.e., years of service since construction or major reconstruction—and accumulated for each year of the analysis period. Kilometers that should have been rehabilitated—i.e., reached P, before the beginning of the analysis period—represent the contents of POTTS.

Cost Calculations

Rehabilitation

The cost of rehabilitation is calculated by taking the kilometers that are overlaid and multiplying the unit cost of overlay for the additional thickness required to obtain the structural number sufficient to sustain the 80-kN ESALs expected during the design life of the overlay.
In addition, the costs for raising the shoulders to the level of the new overlay are also included. These shoulders are categorized as either aggregate or asphalt concrete, and cost for the appropriate type and volume of material is included.

Maintenance

Maintenance costs can be input separately by the user or calculated by using internal models obtained from EAROMAR (6). These models predict routine maintenance items as a function of pavement age:

1. For flexible pavements, skin patching, base and surface repair, and crack sealing; and
2. For rigid pavements, joint sealing, mudjacking, blowups, and concrete surface patching.

These maintenance costs can be allocated in two different ways. First, the maintenance costs are calculated for current load-limit conditions only as a function of age by using regression models obtained from EAROMAR (6). This same set of models can be used to calculate maintenance as a function of age for the same pavements, but performance would be estimated by using loads applied under the new legal load limits. This option would represent a situation in which the level of maintenance funds is historically nearly constant or there are ceiling levels on employment that would prevent the maintenance level from being as responsive to distress in pavements as might otherwise be desired.

The second method for handling maintenance costs may best be called an accelerated maintenance method. This method is based on the assumption that a pavement will receive some prescribed amount of maintenance whether the life cycle is shortened by heavier loads or not. Layton and Hicks (9) used the assumption that cumulative maintenance costs expended on a roadway between initial construction and average time to terminal serviceability do not change with changes in load limits.

The procedure for accomplishing this acceleration of maintenance costs can best be illustrated by using Figure 3, which shows the technique for determining the cost of applied maintenance during each year of the analysis period under a proposed load-limit change. The cumulative maintenance cost shown in Figure 3 is calculated as a function of the age of the pavement by using regression models from EAROMAR. This cumulative cost curve is developed for pavements to present load limits but is also used to determine the amount of maintenance to be charged to each kilometer of pavement for the proposed load limits. The technique used to calculate accelerated maintenance is based on the assumption that the maintenance cost incurred between two different PSI levels is the same but the time during which the maintenance occurs changes. Therefore, as the rate of change of PSI per year increases, a larger increment of maintenance cost is charged to that year.

For example, in Figure 3, during the year between 1 and 1 + 1 and under the proposed load limits, the PSI changed from PSI, to PSI.,. To calculate the accelerated maintenance cost applied to year 1, extend the PSI lines from year, and year, from the proposed load-limit PSI curve to the present load-limit PSI curve. Extend vertically from the intersections of PSI, and PSI,, with the present limit curve to the
cumulative maintenance cost curve. The difference between cumulative maintenance at PSI, and PSI, is the accelerated maintenance applied to year, under the proposed load limits. This level of maintenance under the proposed load limits is larger than the level applied to the same calendar year under present load limits.

SHIFTING OF LOAD DISTRIBUTION

The axle-load distributions for present load limits are shifted in order to evaluate the effect of changes in legal load limits on future truck-weight distributions. To do this, the user should supply the appropriate load information for each of the truck types to be used in the analysis: (a) GVW distribution, (b) single-axle-load distribution, (c) tandem-axle-load distribution, (d) tridem-axle-load distribution, and (e) steering-axle-load distribution. For example, a 3-S2 has a steering axle and two tandem axles; therefore, no single- or tridem-axle-load distributions are necessary and the steering-axle-load distribution is optional input. Once the appropriate axle-load distributions have been input for the present legal limit and the appropriate 80-kN ESALs have been computed, the distributions are shifted to simulate the anticipated effects of changes in legal load limits. If the legal load limits increase, the distributions are expected to shift toward higher loads. The result of such a shift will be that additional payload (GVW minus tare weight) can be carried by each truck and, if the same types of trucks are used with higher axle loads, the life cycle of the pavement will decrease because the damage per loaded truck increases exponentially as the payload increases linearly.

Data on load distributions obtained from W-4 loadometer tables are input into NULOAD and converted to cumulative distributions. An example of this type of information is shown in Figure 4, which represents the cumulative distribution of GVW for the 3-S2 truck. The solid line represents data taken from a W-4 table that has been smoothed. This cumulative distribution is shifted by using a procedure reported by Whiteside and others (3). The result of such a shift is also shown in Figure 4. The individual axle distributions are also shifted by using a procedure similar to that given by Whiteside and others.

Once the axle-load distributions are defined, the number of 80-kN ESALs can be calculated for both present and proposed load limits by multiplying equivalency factors for each weight interval from the AASHTO Interim Guide (4) by the percentage distribution of axle weights.

CHECK FOR CONSISTENCY

The procedure developed by Whiteside and others (3) includes calculation of the average payload for an average truck of each type that has been incorporated in NULOAD. At the point at which the average payload is calculated, the average number of 80-kN ESALs for an average truck of each type is also calculated. The total payload carried by all trucks of each type during each year under present legal load limits can also be calculated. At this point in the NULOAD procedure, the user has the choice of making either the number of trips or the total payload equal under both the present and the proposed legal load limits. If the user selects the equal-payload option, fewer trucks of each type will be required to carry the calculated total payload under the proposed than under the present load limits. If the user selects the equal-trips option, the number of 80-kN ESALs for the proposed legal load limits will be the number of trips of each truck type for present legal load limits times the number of ESALs for an average truck of that type under the proposed load limits. One
should understand that the implication associated with the equal-trips option is that either some freight will be diverted from other modes or that new freight will be generated to supply the extra payload difference between payload for a truck type under present and proposed legal load limits. The equal-total-payload option ensures a fair comparison for the effects of increased weights, whereas the second option, which may be more realistic for the actual situation, does not.

ECONOMIC EVALUATION

Engineering economy studies are conducted because of the need for making a choice between several alternative plans for accomplishing some objective of providing a given service. In order to make a selection between the several alternatives available, there should be a technique for normalizing the costs so that a clear decision between the alternatives can be made. The use of interest to accomplish this normalization and the fact that payments or costs that differ in total magnitude but are made at different dates may be equivalent to one another are both very important in engineering economy (11). To assist the user of NULOAD in making these comparisons, two types of economic analysis calculations are performed and are discussed in the following paragraphs.

Once the maintenance and overlay costs incurred during each year of the analysis period have been computed, they are converted by the use of interest factors to equivalent costs at the same time base. The present worth of all dollars to be spent in future years of the analysis period is calculated separately for both maintenance and overlay rehabilitation costs and for both present and proposed load limits. The ratio of the present worth of costs of maintenance and overlay under proposed load limits to that under present load limits is calculated and included in the output from NULOAD. In addition to the ratio of the present worth of costs, the difference in the present worth of total cost under proposed and present load limits is also included in the output. Because of the difficulty of assessing the worth of the system at the beginning of the analysis period, assessment of salvage value in monetary terms was beyond the scope of this project. However, salvage value is addressed from a structural standpoint by life. This means that the structural condition of the system at the beginning of the analysis period, the present legal limits, and the present worth of costs of maintenance and overlay rehabilitation are calculated and included in the output. In addition to the ratio of the present worth of costs, the difference in the present worth of total cost under proposed and present load limits is also included in the output. Because of the difficulty of assessing the worth of the system at the beginning of the analysis period, assessment of salvage value in monetary terms was beyond the scope of this project. However, salvage value is addressed from a structural standpoint by life. This means that the structural condition of the system has been improved as a result of overlay expenditures required to carry loads resulting from the load-limit changes.

As would be expected, the cost ratios are identical for the present-worth and uniform annual cost results. In the context of uniform annual cost, the increased cost of maintenance and rehabilitation on the 1776 lane-km (1101 lane miles) of flexible pavements is approximately $257/lane-km ($413/lane mile) more annually and, for the 3574 lane-km (2220 lane miles) of rigid pavement, the costs are increased by $292/lane-km ($470/lane mile) annually. On a system basis, this is a weighted value of approximately $280/lane-km ($451/lane mile) more annually. Although these numbers cannot be verified, the predictions are reasonable.

Tables 2 and 3 demonstrate some of the more detailed information concerning the calculation of the summary costs given in Table 1. In the procedure, five major tables for each of the representative sections are provided. They include (a) present and proposed regulations (Tables 2 and 3), (b) discounted cost tables, including maintenance, overlay, and total costs estimated for both present and
Table 1. Differences between present and proposed legal load limits.

<table>
<thead>
<tr>
<th>Section</th>
<th>Kilometers</th>
<th>Delta Present</th>
<th>Cost Present</th>
<th>Uniform Annual</th>
<th>Delta Uniform</th>
<th>Cost Uniform</th>
<th>Ratio Remaining Life (proposed limits/present limits)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td>Delta Uniform</td>
<td>($000s)</td>
<td>Uniform Annual</td>
<td>($000s)</td>
<td>Life</td>
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<td>19953.25</td>
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<td>1633.99</td>
<td>1.34</td>
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<td></td>
<td>17171.49</td>
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</table>

Note: 1 km = 0.82 mile.

Table 2. Performance table for proposed load regulations.

<table>
<thead>
<tr>
<th>Kilometers</th>
<th>Year of</th>
<th>Overlay Design</th>
<th>Overlay Thickness</th>
<th>PSI at End of Analysis Period</th>
<th>Remaining Life (millions 80-kN ESALs)</th>
<th>Overlay Cost ($/lane-km)</th>
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</thead>
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</table>

Note: 1 km = 0.82 mile; 1 cm = 0.39 inch; $1/lane-km = $1.61/lane mile.

Table 3. Performance table for proposed load regulations.

<table>
<thead>
<tr>
<th>Kilometers</th>
<th>Year of</th>
<th>Overlay Design</th>
<th>Overlay Thickness</th>
<th>PSI at End of Analysis Period</th>
<th>Remaining Life (millions 80-kN ESALs)</th>
<th>Overlay Cost ($/lane-km)</th>
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Note: 1 km = 0.82 mile; 1 cm = 0.39 inch; $1/lane-km = $1.61/lane mile.

proposed load limits. The following information is also provided:

1. The predicted increase in payloads and number of 80-kN ESALs by truck type and
2. The final shifted axle-load distributions, which can be compared with the input distributions to determine the effect of the shift.

SUMMARY

NULOAD is an implementable program that evaluates the effects of potential new legal load limits in terms of pavement maintenance and rehabilitation costs. Different axle configurations—such as tridems—or different truck sizes—such as triple-trailer units—can be evaluated. NULOAD cost predictions can be combined with benefit predictions to allow for a rational study of the effect of proposed legal limits on pavement costs. Complete documentation of the development of the procedure is available elsewhere (1). A user's manual has been prepared to provide the information necessary for using NULOAD, including (a) a summary description of the procedure, (b) a list and description of all inputs and outputs, (c) a complete illustrative problem, and (d) a detailed input guide (2).

NULOAD can be used to evaluate a city, a county, a district, or a state. It is conceivable that, if solutions were prepared for all 50 states, a prediction for the United States could be prepared. Other potential applications of the NULOAD program include an analysis of truck route networks, consideration of a modal shift in commodity hauling, and an evaluation of the effect of...
different analysis periods on the failure of existing pavement and overlay life.

ACKNOWLEDGMENT

The work presented in this paper was accomplished in 1978 by a team that included R. Frank Carmichael III, Freddy L. Roberts, Peter R. Jordahl, Harvey J. Treybig, Harold Von Quintus, Larry L. Caldwell, Russell Catalano, Fred N. Finn, and W. R. Hudson. We wish to thank Peter R. Jordahl for his leadership in the development of analytical techniques and in the computer coding and other members of the team, including Harold Von Quintus, Larry L. Caldwell, and Russell Catalano, for providing development support. We especially thank F. N. Finn and W. R. Hudson for providing technical consultation.

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REFERENCES


Heavy Trucks on Texas Highways: An Economic Evaluation

C. Michael Walton, Department of Civil Engineering, University of Texas at Austin
James L. Brown, Asphalt Institute, Austin, Texas
Dock Burke, Texas Transportation Institute, Texas A&M University, College Station

A study undertaken to assess the effects of projected truck traffic on the highway system of Texas is described. The study included the evaluation of costs and benefits for a 20-year planning horizon. Alternative scenarios of future truck traffic were assessed. The study considered only an increase in gross vehicle weights and axle loads and not the effects of changes in the size of trucks or the effects of heavy trucks on county roads and city streets. The major approach to the study involved estimating the comparative pavement maintenance and rehabilitation costs of perpetuating the state highway system under current weight limitations and of future use under different weight conditions. It is concluded that, if changes in weight laws are undertaken, further analysis will be needed to select those routes that would carry relatively large freight tonnages and cost relatively less to upgrade.

The objective of this study was to assess the effects of projected truck traffic on the Texas highway system for a 20-year analysis period. Selected costs and benefits were calculated to show some of the measurable effects of increasing the legal weight limits for trucks that operate on the state network.

The study included the evaluation of costs and benefits for a 20-year planning horizon. Alternative scenarios of future truck traffic were assessed. The study did not consider the effects of changes in the size of trucks, only an increase in gross weights and axle loads. The study did not evaluate the effects that heavy trucks would have on county roads or city streets.

SELECTION OF SCENARIOS

The identification of alternative scenarios was accomplished through analysis, discussion, and evaluation of


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